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# **Keeping the Fly Ash out of the Stack**

**(U.S.) Industrial Environmental Research Lab, Research Triangle Park, NC**

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| 16. ABSTRACT<br>This paper discusses results of tests conducted by EPA on the efficiency of hot-side electrostatic precipitators in controlling SOx and fly ash emissions from industrial boilers. In this case, Unit 3 of Duke Power Company's Allen Steam Station was used for the tests. Test methods used on the hot-side ESPs were EPA sanctioned. Replicated tests were made over a 8 day period. Efficiency of the hot-side ESPs depended on the size of the particle to be collected. Efficiency was 99.8% at 4 micrometers; 99.5% at 8 micrometers; and 98% at 0.6 micrometers. The average efficiency percentage was 99.69%. Results of the tests also indicated that the location of the ESP on the hot side of the air preheater greatly increased the efficiency of particulate collection. |                                                                                                    |                                                              |
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Keeping the Fly Ash out of the Stack

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Over the past several years, many electrical utilities and industries have shifted to low-sulfur coal as a primary fuel, in order to reduce their atmospheric emissions of sulfur oxides ( $\text{SO}_x$ ). This trend has alleviated the targeted  $\text{SO}_x$  emission problem, but has conflicted with another pollution control operation; namely, the collection of particulate fly ash from the combustion process.

## Why these tests were run

To gather data on one method that is being used to achieve high-efficiency particulate control with low-sulfur coal, EPA recently conducted an intensive test program on a hot-side electrostatic precipitator (ESP) of moderate size. The ESP controls particulate emissions from Unit 3 of Duke

Power Company's Allen Steam Station. The tests showed the precipitator efficiency to be well above 99%, while the boiler was burning 0.93–1.04% sulfur coal.

The highest collection efficiency was observed at the 4  $\mu$  particle size. The efficiency of collecting submicron particles was slightly lower, in accordance with frequently observed behavior; the efficiency at 8  $\mu$  was slightly lower because of rapping re-entrainment losses.

### Contending with resistivity, a very critical factor

Electrostatic precipitation is currently the prevalent method of controlling particulate emissions from large coal-burning boilers. The electrical resistivity of the ash is a critical parameter in the design and operation of a precipitator. At temperatures below 200 °C, surface conduction is generally considered to be the controlling factor that determines the resistivity of fly ash. The resistivity of the ash is thus dependent on the physical characteristics of the particles' surface; on the content of  $\text{SO}_3$ ,  $\text{Na}_2\text{O}$ , and other hydrophilic compounds in the ash; and on the water vapor pressure in the flue gas.

Fly ash produced from combustion of low-sulfur coal contains relatively little absorbed  $\text{SO}_3$ , and normally exhibits relatively high electrical resistivity. High-resistivity ash often necessitates a reduction in the applied voltage and resulting current density in a precipitator, in order to avoid excessive sparking rates. Collection efficiency may then suffer because of the increased charging times required under lower current conditions, and the reduced field. In extreme cases in which the applied voltage is forced to a high level, back corona (also called secondary emission or reverse ionization) occurs, and severely disrupts the collection process.

To compensate for the unfavorable operating conditions that are common with high-resistivity ash, the size of the ESP can be increased. Also, chemical conditioning agents can be added to the flue gas to reduce the ash resistivity artificially. Both of these practices have been commercially applied.

A third alternative is to increase the operating temperature of the precipitator. At temperatures above 300 °C, volume conduction prevails over surface conduction; resistivity is more dependent on bulk chemical composition of the ash, rather than on surface peculiarities, adsorbed species, or hydrophilic action. The resistivity at these higher temperatures is usually less dependent on fluctuations in fuel composition and is almost always low enough to allow efficient precipitation.

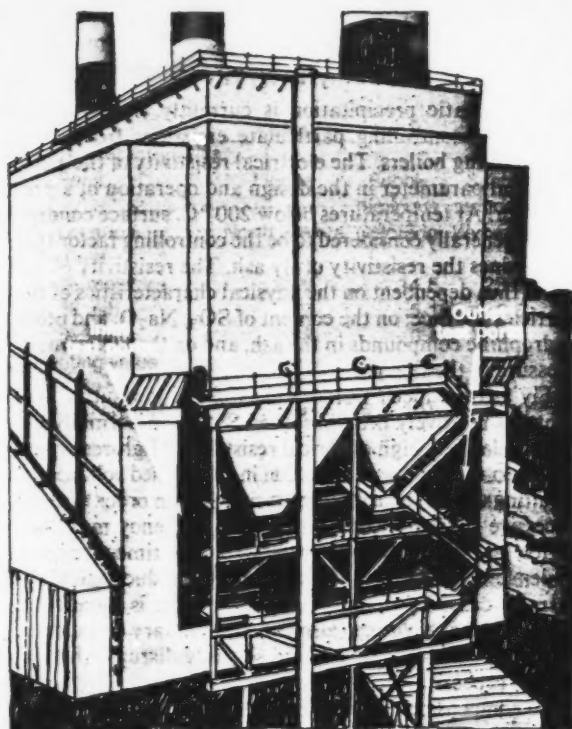
### How costs stack up

However, the ultimate factor that determines which alternative a user selects to achieve or maintain high-efficiency particulate collection is normally economics. The annual costs to own and operate a precipitator are affected primarily by the size of the unit, the construction materials required, power consumption, ash-handling considerations, maintenance requirements, and reliability. In some cases in which the composition of the fuel supply over the operating life of the precipitator is poorly defined, hot-side precipitators may offer greater long-term reliability, because of their relative insensitivity to fuel consumption.

Since the late 1960's, about 100 high-efficiency ESP's have been installed in power plants on the hot side of the combustion air preheaters, where the flue gas temperature is typically greater than 300 °C. One such installation

controls the fly ash emissions from Unit 3 of Duke Power Company's Allen Steam Station near Charlotte, N.C. With the gracious cooperation of Duke Power, EPA conducted an intensive test program at the Allen installation in 1976, as part of an American/Soviet environmental technology exchange program. The objectives were to study the oper-

ating characteristics of a full-scale high-efficiency hot-side ESP, and to quantify and characterize the flue gas and fly ash physically and chemically.



Precipitator. This one was "shaken down" at Duke Power

## The test site

Allen Steam Station has five coal-burnin, single-reheat, steam-electric generating units. Units 1 and 2 have nameplate capacities of 165 MW each, and Units 3, 4, and 5 are rated at 275 MW each. Each of the five units has a rated main steam pressure of 16.65 meganewtons (MN)/m<sup>2</sup> (2415 pounds-force (lbf)/in.<sup>2</sup>) gauge; a superheat temperature of 566 °C (1050 °F); and a reheat temperature of 538 °C (1000 °F). Units 3, 4, and 5 at Allen Steam Station are identical, including the precipitator installations. Unit 3 was chosen as the test unit after consideration of maintenance outage schedules and test area access of the three units.

Commercial operation of Allen Unit 3 began in 1959. Although the unit has a nameplate rating of 275 MW, it has frequently been operated at a gross load of 300 MW, or slightly higher. The unit auxiliaries utilize approximately 6.5% of the generated power, so that the net efficiency of Allen Unit 3 is approximately 35.9% (heat rate of 9500 Btu/net kWh).

At a gross load of 275 MW, the thermal input to the boiler is approximately 716 MW (2440 × 10<sup>9</sup> Btu/h). Although it varies a few percent with the heating value of the coal, the coal-firing rate at a 275-MW gross load is roughly 100 metric tons/h (220 000 pounds-mass (lbm)/h). Table 1 lists coal characteristics of low-sulfur eastern coal burned at Duke Power plants including Allen Unit 3.

FIGURE 1

### Flue gas system

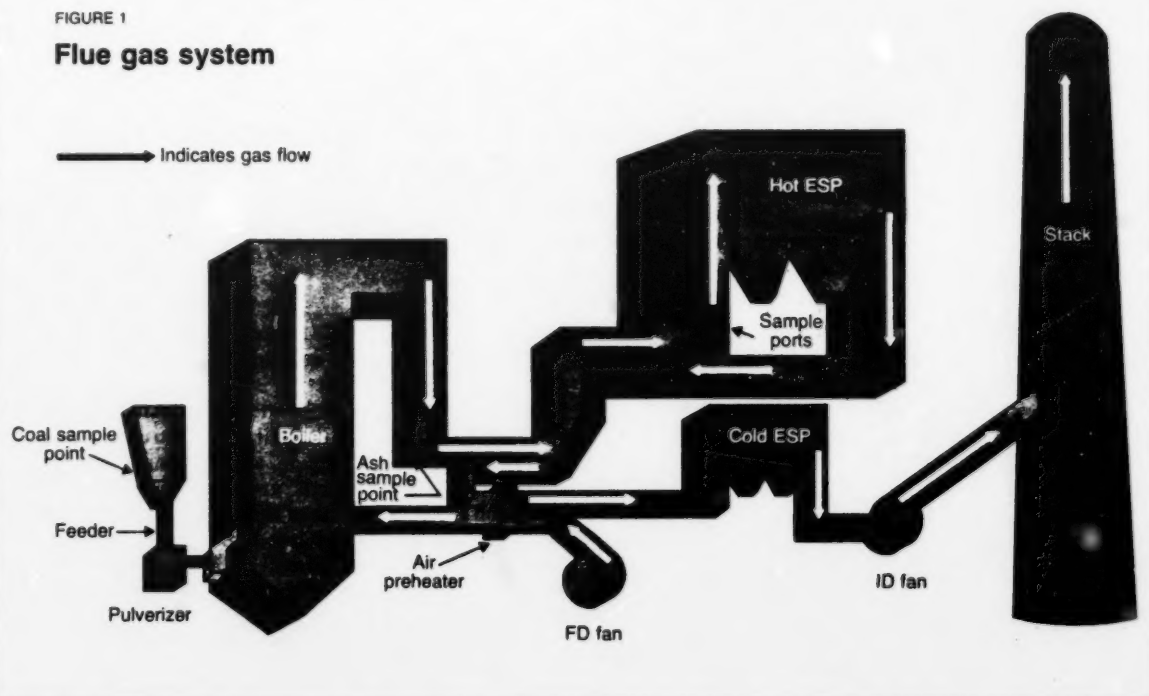


TABLE 1

**Typical coal analysis at Plant Allen**

|                             |                                        |
|-----------------------------|----------------------------------------|
| Higher heating value        | 25.2-27.3 kJ/g (10 850-11 750 Btu/lbm) |
| Ash content                 | 15-18%                                 |
| Sulfur content              | approximately 1%                       |
| Moisture content (as fired) | 6-9%                                   |

About 25% of the ash falls out in the dry-bottom boiler as bottom ash. The remaining 75% of the ash leaves the boiler with the hot flue gases. As shown schematically in Figure 1, the gases flow first through the hot-side electrostatic precipitator at about 343 °C (650 °F). Then they go through the air preheater where the gas temperature is lowered to approximately 138 °C (280 °F) by preheating the incoming combustion air. The flue gases then flow through the cold-side ESP before the pressure is raised by the induced draft fan, and the gases exit to the atmosphere through the 77-m (252-ft) stack.

**Hot-side ESP: what it looks like, how it works**

During its original construction, Allen Unit 3 was equipped with a cold-side electrostatic precipitator designed to remove 97% of the fly ash from the flue gases. In the late 1960's Duke Power Company began a program to upgrade the particulate emission controls on many of its coal-fired units. By that time, both utility companies and precipitator manufacturers had gained sufficient experience to realize that high-resistivity ash was a major detriment to operating ESP's with high collection efficiencies. The important effects that fuel composition and flue gas temperature have on ash resistivity were also coming into perspective.

Duke Power chose to improve some of its units by installing additional cold-side precipitators in a series or parallel configuration with the existing control equipment. For other units, including Unit 3, new hot-side precipitators were designed and installed. Startup of the precipitator on Allen Unit 3 occurred in March 1973.

The cold-side precipitator also remained in service, although the hot-side unit was designed to achieve 99.2% efficiency with expected inlet ash loadings. With low inlet loadings, the hot units was guaranteed to achieve an outlet concentration no higher than 46 mg/m<sup>3</sup> (0.02 gr/acf).

In that hot-side ESP, there are four parallel chambers for gas flow, and each chamber consists of four sections in series. Separate ducts carry flue gases into and out of the four chambers. The two center chambers are separated internally by a gas-tight partition, dividing the precipitator into two completely separate sides. In each of the two sides, the eight sections are supplied with power from four transformer-rectifier (T/R) sets. Each of the two parallel sections that is supplied by a single T/R set can be electrically isolated. Table 2 gives additional design specifications of the hot-side electrostatic precipitator.

**Cleaning the ash out, and settling it**

Ash deposits are removed from the wires by vibrators that have an adjustable cycle of operation. Each vibrator is normally operated twice every half-hour, with an approximately 90-s delay between the two vibration periods. Each vibration period lasts 6 s.

The plates are cleaned by solenoid-activated hammer-

TABLE 2

**Hot-side electrostatic precipitator specifications**

|                                |                                                                                                                                                                                                                                                                                                                            |
|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Manufacturer                   | Research-Cottrell, Inc., Bound Brook, N.J.                                                                                                                                                                                                                                                                                 |
| Startup date                   | March 5, 1973                                                                                                                                                                                                                                                                                                              |
| Design gas flow                | 590 actual m <sup>3</sup> /s (1 250 000 actual ft <sup>3</sup> /min)                                                                                                                                                                                                                                                       |
| Design gas velocity            | 1.81 m/s (5.94 ft/s)                                                                                                                                                                                                                                                                                                       |
| Design-specific collector area | 53 m <sup>2</sup> per actual m <sup>3</sup> /s (270 ft <sup>2</sup> per 1000 actual ft <sup>3</sup> /min)                                                                                                                                                                                                                  |
| Design efficiency              | 99.2%                                                                                                                                                                                                                                                                                                                      |
| Overall configuration          | 4 parallel chambers<br>4 sections in series per chamber<br>39 parallel gas passages per chamber                                                                                                                                                                                                                            |
| Plates                         | 40 plates per chamber (cold rolled steel sheets)<br>Plate height is 9.14 m (30 ft)<br>Plate length each section is 2.74 m (9 ft) for total length in direction of flow of 10.97 m (36 ft)<br>Plate-to-plate spacing is 0.229 m (9 in.)<br>Total surface area of plates is 31 305 m <sup>2</sup> (336 960 ft <sup>2</sup> ) |
| Wires                          | 48 equally spaced wires per gas passage (hand drawn Bessemer steel with coppered surface)<br>Wire diameter is 2.77 mm (0.109 in.)<br>Wires are hanging type, placed in the center $\pm$ 6.35 mm ( $\frac{1}{4}$ in.) of the plate-to-plate space                                                                           |
| Electrical                     | 8 transformer-rectifier sets<br>16 electrically isolatable bus sections<br>Transformer rating is 96 kVA<br>Rectifier rating is 1500 mA<br>Wave form is double/half full<br>Normal power consumption is approximately 580 kW, 720 kW is maximum consumption                                                                 |

type rappers. Each rapper is activated at least once every 2 min, and some are activated twice every 2 min. The approximate rapping intensity is 32.5 J (24 ft-lbf). The collected ash falls into hoppers beneath the precipitator. It is periodically removed from the hoppers by a dry, pressurized ash-handling system and flows to a collecting tank from which it is water-slurried to an ash-settling basin.

**Test methods**

*They were exhaustive, and used procedures sanctioned by the EPA*

The test program at Plant Allen involved the measurement of several parameters by standard EPA methods, or by state-of-the-art procedures in those cases in which standard methods have not been promulgated. Replicate runs were made over a period of 8 days. Before each day's tests began, ash was removed from the precipitator hoppers,

and boiler soot blowing was conducted. During the actual sampling, both of those operations were suspended.

#### Getting the samples—gas and ash

At half-hour intervals throughout each day of testing, operational data from the steam-electric generating unit and the electrostatic precipitator were monitored from inside the plant. In the control room from which Units 1, 2, and 3 are operated, charts continuously recorded unit operating parameters, such as electrical load, fuel flow, air flow, steam flow, and flue gas temperatures and pressures.

The oxygen concentration of the gas was also continuously recorded in the control room. Periodically, it was also manually checked with a portable recorder at several duct sample lines.

There are eight control panels for the Unit 3 hot-side precipitator, one for each transformer-rectifier set. From instrument displays on these panels, readings were made of the transformer primary voltage (a.c.), the transformer primary current (a.c.), the precipitator average current (d.c.), and the precipitator spark rate.

At 20-min intervals during each test, individual coal samples were collected at each of 12 sample points at the hoppers located above the coal pulverizer feeders (Figure 1). The coal corresponding to each test was then made into composite samples, systematically divided into smaller samples, pulverized, and air dried. Tests were conducted to determine the heating value, and the composition of ash, moisture, sulfur, carbon, hydrogen, nitrogen, and oxygen.

Fly ash samples were also collected during each test. One sample was collected from each of the two boilers associated with Unit 3. The sample point for each boiler was located downstream of the economizer, where the flue gas turns from vertical down flow to horizontal flow (Figure 1). The two samples from each test were composited and subjected to quantitative chemical analyses.

The tests that required sampling of the gas upstream and downstream of the hot-side ESP actually involved only one-half of the complete precipitator that controls emissions from Unit 3. The precipitator is internally separated into halves by a gas-tight partition. Eight sampling ports were located in the vertical sections of each of the ducts leading into and out of certain chambers of the precipitator, and 24 test points were defined for each duct. One port on the inlet side of one of the ducts could not be sampled, because of a physical obstruction. Prior to the other tests, the flue gas velocity profile and static pressure were measured in each duct by using S-type pitot tubes (EPA Method 2, *ES&T*, July 1977, p 657).

#### Collection efficiency

To determine the precipitator collection efficiency, mass sampling was conducted at the inlet by using the standard EPA Method 5, and at the outlet by using a high-volume EPA Method 5 train. The flue gas moisture content was determined at the inlet by Method 5, concurrent with the mass sampling. Flue-gas molecular weight was determined from samples extracted with a separate Orsat probe (EPA Method 3) attached to the mass-sampling probe.

Particle-size distributions were determined on the inlet with Brink impactors, and on the outlet with Andersen impactors. Outlet samples were obtained by complete transverses of the two outlet ducts. Because of a combination of short sampling times and poor inlet velocity distri-

butions, the inlet samples were obtained from individual ports, extracting one sample from each of four ports in each inlet duct.

#### SO<sub>x</sub> determination

SO<sub>2</sub> and SO<sub>3</sub> concentrations of the inlet gas were determined by EPA Method 8. That method is based on the absorption of SO<sub>2</sub> and SO<sub>3</sub> from an extracted flue-gas sample, followed by laboratory measurement with the barium chloride/thorin titration method. The apparatus is similar to the Method 5 train, except for the contents of the impingers.

SO<sub>3</sub> is absorbed into isopropyl alcohol in the first impinger. The filter is later added to this solution for extraction of the SO<sub>3</sub> adsorbed on the ash. The second and third impingers contain hydrogen peroxide which absorbs the SO<sub>2</sub> from the gas.

#### Ash resistivity measurement *in situ*, with a point-to-plane probe

Fly ash resistivity was measured with an *in-situ* point-to-plane-type resistivity probe developed by Southern Research Institute (Birmingham, Ala.). Separate ports, located in the horizontal segment of the inlet ducts about 3 m (10 ft) from the other inlet ports, were used for the resistivity testing. To use the point-to-plane resistivity probe,



Test run. Setting up a fly ash resistivity probe

the probe was lowered into the duct, and a thin layer of dust was deposited by electrostatic precipitation. The resistivity of the dust was then determined by measuring the voltage-current relationship across the thin layer.

Readings from the precipitator control panels located inside the boiler building, and on top of the precipitator, were monitored during two special tests to check for the presence of back corona. The Soviet-devised procedure involves varying the secondary voltage to the precipitator and recording the corresponding secondary current. By studying the relationship between these two parameters, one can detect the occurrence of back corona.

## Test results

The first six tests were conducted on the entire half of the precipitator serviced by certain ducts designated as B-1 and B-2. Test 7 was conducted on duct B-2 only, and test 8 on duct B-1 only. For the first six tests, the average inlet gas flow, as measured during the Method 5 test, was 11 440 actual cubic meters per minute (acmm) or 403 950 actual cubic feet per minute (acfm), with a standard deviation of 191 acmm (6740 acfm). The outlet flow averaged 12 977 acmm (458 230 acfm), with a standard deviation of 212 acmm (7490 acfm). These results indicated an increase in gas flow of 13% from the inlet to the outlet.

### Dealing with discrepancies

This discrepancy was partially explained by air leakage into the inlet test ports, or into some other openings between the inlet and outlet test ports. This hypothesis was supported by the consistently higher oxygen readings measured at the outlet.

Another factor that probably contributed to the discrepancy was the omission from sampling of the obstructed port on duct B-1 at the inlet. The gas passing this port was assumed to have a velocity equal to the duct average, for the purpose of gas volume calculation. But preliminary velocity traverses indicated that the actual velocity at the port was about 22% higher than that of the duct average.

The precipitator collection efficiency averaged 99.69% over the eight tests, with a standard deviation of 0.08%. The inlet total mass concentration averaged 4.94 g per actual cubic meter (g/acm), or 2.16 grains per actual cubic foot (gr/acf), with a standard deviation of 0.32 g/acm (0.14 gr/acf). The outlet total mass concentration averaged 15.06 mg/acm (6.58 gr/1000 acf) with a standard deviation of 3.58 mg/acm (1.68 gr/1000 acf). The results showed very good reproducibility, with a coefficient of variation of less than 10% at the inlet, and about 25% at the outlet.

### Particle sizes collected

Results derived from the Brink and Andersen data indicated a maximum fractional collection efficiency of 99.8% at 4  $\mu$  (aerodynamic diameter). The efficiency decreased for larger and smaller particles to 99.5% at 8  $\mu$  and to 98% at 0.6  $\mu$ . The decline in efficiency at smaller sizes is consistent with the frequent observation in precipitators and other collection devices of a minimum in efficiency in the 0.1–1  $\mu$  particle size range. The slight decline in efficiency at larger sizes and the relatively high mass median diameter (MMD) on the outlet indicate that rapping re-entrainment losses contribute significantly to the emissions from the precipitator. Nevertheless, the overall precipitator efficiency is sufficiently high that the re-entrainment losses are inconsequential.

Six SO<sub>x</sub> tests were conducted, coinciding with the first six particulate mass tests. On a dry basis, the SO<sub>3</sub> results averaged 2.38 ppm by volume, with a standard deviation of 1.91 ppm, and the SO<sub>2</sub> concentration averaged 818.2 ppm with a standard deviation of 124.0 ppm. The low concentration of SO<sub>3</sub> would provide little natural condi-

tioning to lower the ash resistivity in a cold-side precipitator.

### Resistivity values

Results of the fly ash resistivity tests conducted with the *in situ* probe showed an average value of  $1.9 \times 10^{10}$  ohm-cm. That is close to the reported level for incipient back corona. However, the Soviet-devised back corona test showed no evidence of back corona on either occasion that it was conducted, and the efficiency results certainly indicate satisfactory precipitator performance.

The coal analysis showed reasonable agreement with the expected characteristics noted in Table 1. The air-dried samples from the eight tests had a moisture content averaging 0.98%, an ash content averaging 13.6%, and a heating value averaging 28.8 kJ/g (12 380 Btu/lbm).

The collection technique used to obtain the fly ash samples was not set up to provide a completely representative sample in terms of size distribution. Since the chemical analysis of fly ash in a single boiler generally varies to some extent with particle size, results may not be precisely indicative of the composition of ash collected by the precipitator, or of the small quantity of ash remaining in the stack gas.

### Hope for western coal

The results of the foregoing tests demonstrate that location of the precipitator on the hot side of the air preheater is a successful method of achieving high efficiency particulate collection despite the use of low-sulfur coal. Hopefully, they also indicate one way in which better, wider, and cleaner use of the vast supplies of coal in the western states can be made.

### Additional reading

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